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The relative visibilities of spatial variations in luminance and chromaticity

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THE RELATIVE VISIBILITIES OF SPATIAL VARIATIONS IN LUMINANCE AND CHROMATICITY

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SUMMARY

An optical method of producing sinusoidal (spatial) variations of the colour of an illuminated screen is described. Either colour variations of chromaticity at constant luminance or colour variations of luminance at constant chromaticity can be selected. An observer viewing the screen can control the magnitude of the colour variation - and hence its visibility. By making visually-equivalent judgments, his relative sensitivity to the two forms of colour variation can be measured.

The results obtained by a group of ten observers for a range of test colours are presented, and their dependence on several factors is briefly investigated.

1. INTRODUCTION

One of the basic features of the compatible NTSC colour television system is the adoption of the 'constant luminance' principle.[1] One advantageous result of the application of this principle is that any interference or random noise introduced in the chrominance channels of the system will result in the least visible kind of perturbation of the displayed colour picture. Early experiments[1] showed that this condition would be met if the two chrominance signals transmitted were so chosen that a perturbation of one or both signals would result in a corresponding perturbation of only the chromaticity of the picture, the luminance remaining undisturbed. A commonplace generalization thus arises - that the eye is more sensitive to spatial and temporal variations in luminance than to variations in chromaticity. Outside the context of a specified system, e.g. a three-colour additive system, the above generalization is clearly meaningless because luminance and chromaticity variations cannot be expressed objectively on the same physical scale. However, in terms of a convenient reference framework, it is of great interest to determine the relative magnitudes of the variations in chromaticity or luminance which would be judged to be visually equivalent. Further data on how these relative magnitudes depend on the chromaticity, absolute luminance and on other factors will be of value. For example, such data would enable a more comprehensive assessment to be made of the advantage of the 'constant luminance' principle in colour television systems.*

* The application of the results presented in this report to the colorimetric analysis of interference in colour television will be considered in a further report.

The purpose of the optical experiments reported here was to obtain some basic information on the visibilities of spatial, sinusoidal variations of colour: a similar type of variation in a colour television receiver could arise, for example, from an unwanted carrier having a frequency near that of the colour subcarrier in a colour television emission.

The existing data obtained by MacAdam[2] on the just-noticeable differences in chromaticity between the two halves of a bipartite visual field provides a valuable guide to the expected variation of just-noticeable chromaticity deviations as a function of chromaticity. One outcome of MacAdam's work has been the recent adoption by the C.I.E. of his proposal for a uniform chromaticity diagram in which just-noticeable differences in chromaticity have approximately the same vector length. Thus an obvious choice of reference diagram on which to express the results of the experiments described below, is the C.I.E. uniform-chromaticity-scale diagram.

2. OPTICAL EXPERIMENTS

2.1. Object of the Experiments

Suppose that an additive mixture of two primary 'lights' uniformly illuminating a viewing screen produces a particular colour. The colour may be represented as a point (e.g. C in Fig. 1) in a three-dimensional space having co-ordinates V_1, u_1, v_1 with reference to the rectangular set of axes V, u, v, where u and v are the C.I.E. uniform chromaticity co-ordinates and V is the luminance of the colour. A property of this particular reference framework is that planes of constant luminance are parallel to the (u, v) plane, and colours of the same chromaticity lie on lines parallel to the V axis. Suppose that the primary 'lights' are perturbed by a small amount in such a manner that a spatial, cyclic, variation of luminance is seen across the screen (this would appear as a vertical bar pattern similar to that shown in Fig. 2(a)), the chromaticity remaining uniform. Hence a plot of the cyclic excursion of the colour C in Fig. 1 would appear as a short line through C parallel to the V axis. Alternatively, we may suppose that the perturbations are introduced so that a spatial, cyclic, variation of chromaticity is produced on the screen (see Fig. 2(b)) the luminance remaining uniform. The corresponding plot of C in Fig 1 is now a cyclic excursion along a short line through C parallel to the (u, v) plane. If an observer viewing the screen is given a control by which the magnitudes of these luminance-only or chromaticity-only excursions can be varied over a suitable range, he can make settings corresponding to his own judgment of visual equality. From the average of control settings registered by a number of observers the corresponding average lengths of the vectors in the (V, u, v) colour space can be deduced for each condition of the experiment. A range of colours of various absolute luminances and chromaticities can be investigated. Also, using the same observers if possible, the

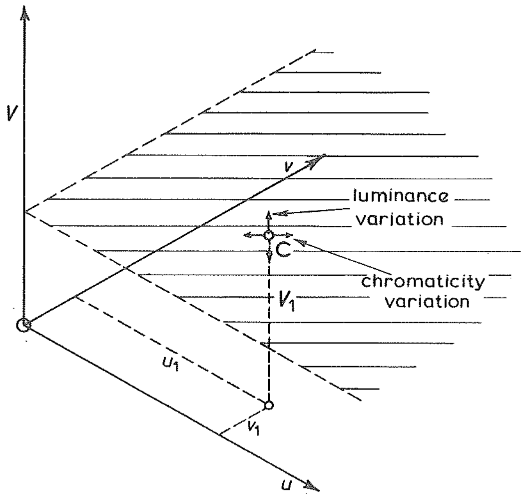
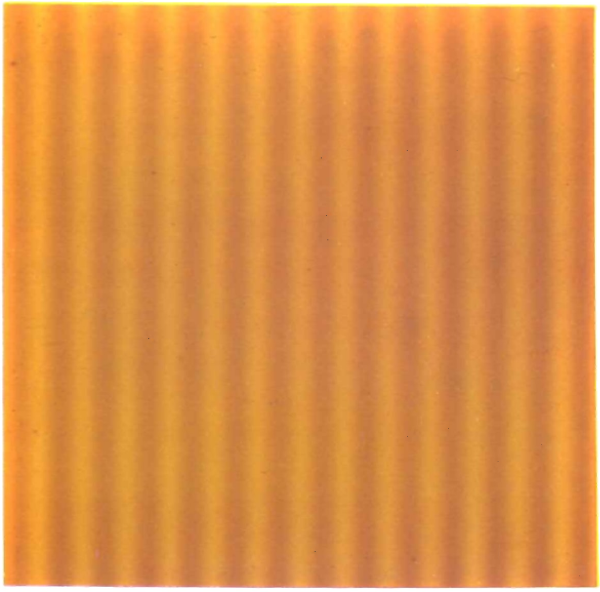
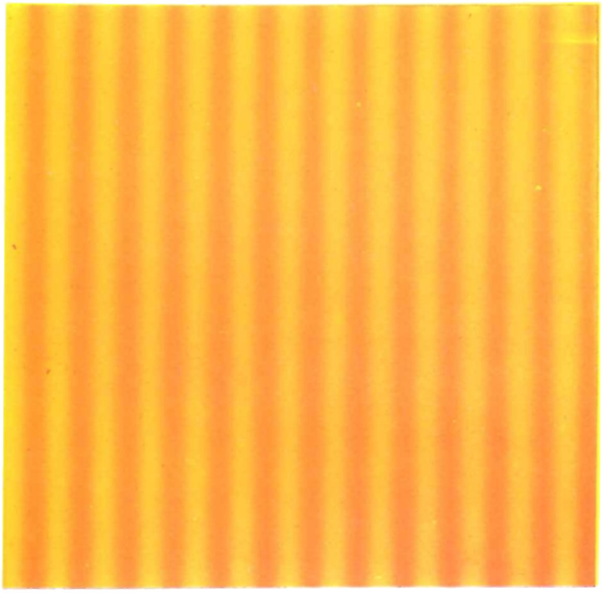


Fig. 1 - (V, u, v) Colour reference space



(a)



(b)

Fig. 2 - Photographs of the test patch showing the two forms of colour variation

(a) Luminance varying - chromaticity uniform

(b) Chromaticity varying - luminance uniform

viewing distance can be altered and any influence this may have on the equality judgements determined. In fact there are almost limitless possible combinations of these and other parameters which can be investigated.

2.2. Optical Arrangement

An optical arrangement was devised to provide a display suitable for the study of the sinusoidal colour variations outlined above. The principle of the method is that, under certain conditions, the superposition of two incoherent light beams impinging on a screen, each beam being sinusoidally modulated in intensity at the same frequency, can produce colour variations ranging from either pure chromaticity variations to pure luminance variations depending on the relative phases of the respective modulations of intensity. The principle can, in fact, be applied to produce variations in either time or space. However, spatial variations were used in the present experiments and these were obtained by modulating the light beams by means of a sine-wave grating near the viewing screen and common to both beams, as shown in Fig. 3(*a*).

Two projector lamps, S_1 and S_2 in Fig. 3(*a*) whose filaments are mutually separated by approximately 2 in. (50 mm), are placed 24 in. (610 mm) from a small viewing screen 2½ in. (60 × 60 mm) square. By interposing two different colour filters, F_1 and F_2, the spectral characteristics of the light falling on the viewing screen from S_1 and S_2 respectively can be modified. Thus the sources are converted into selected colour primaries and, when the amount of each primary has been established, the chromaticity of the additive mixture on the screen can be readily deduced.

Situated at 4 to 5 in. (100 to 125 mm) behind the viewing screen is a large sine-wave grating (photographic transparency) mounted on a 'Vee' slide running on a length of optical bench: the grating-to-screen separation is thus adjustable. It will be seen from Fig. 3(*a*) that when the grating is in position A the coloured rays from each source arriving at a point Q on the viewing screen intersect the grating at points of identical transmission. This is the 'in phase' condition and produces mainly luminance variations across the screen, since the angle subtended by the lamp filaments at any point on the screen is substantially invariant. Alternatively, when the grating is in the position B, approximately 1 in. (2·5 cm) farther away from the screen, the rays from the two sources intersect the grating at antiphase points of its sinusoidal transmission characteristic. This grating position produces sinusoidal deviations of chromaticity with respect to the mean chromaticity of the displayed colour if the luminances of the components in the additive mixture are made equal (e.g. by combining neutral density filters with the colour filters, F_1 and F_2).

The spatial frequency of the pattern produced on the screen, by the particular sine-wave grating used throughout the experiments, was approximately 2 cycles per centimetre There is a small increase (5%) in the spatial frequency when the grating is shifted from position B to position A, which is just-perceptible.

The arrangement described so far allows either luminance-only or chromaticity-only colour variations to be selected by a simple displacement of the grating but the magnitude of the variations is not continuously variable. The latter facility is achieved by the optical arrangement shown in Fig. 3(*b*). The illumination from a second pair of lamps, S_3 and S_4 via a second pair of colour filters, F_3 and F_4,

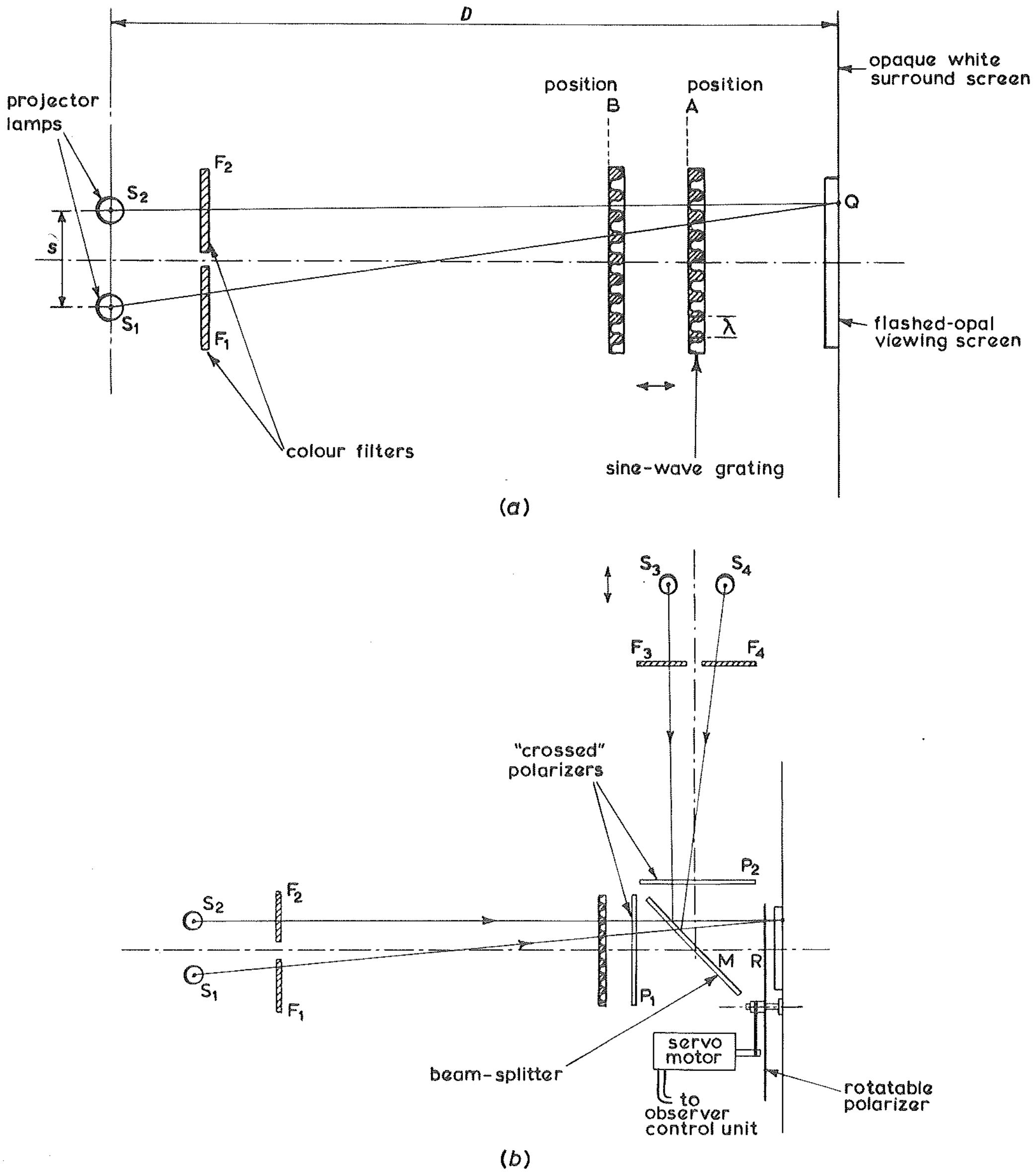


Fig. 3 - Optical arrangement for producing sinusoidal colour variations

is directed on to the viewing screen by means of a semi-transparent beam-splitting mirror, M. This side-arm configuration of lamps and filters is similar so that of the main-arm without the sine-wave grating. Hence, if the light from the main-arm is totally obscured, a uniform patch of colour will be displayed having a chromaticity identical to that produced by the main-arm alone. If a small proportion of the light from the main-arm is allowed to reach the viewing screen the spatial variations or pattern due to the grating will begin to appear. An obvious experimental requirement is that the average total luminance of the displayed colour remains substantially constant. This was achieved by using a 'crossed polarizer' technique. Two Polaroid filters, P_1 and P_2 are placed in each arm of the apparatus respectively, as shown in Fig. 3(*b*). The polarizers are oriented so that their polarizing axes are at right angles. Immediately behind the viewing screen is a large rotatable Polaroid disc, R,

rotating about an axis offset from the centre of the viewing screen. Thus, by means of the polarizing system P_1, P_2 and R, the relative proportions of the illumination from the two arms of the apparatus and, therefore, the deviation amplitude of the colour variations can be varied by adjusting the orientation of the disc polarizer, R. A pointer attached to the edge of the disc polarizer, and running over a fixed angular scale, serves to indicate the orientation of the polarizing axis.

It is shown later in Section 2.4 that if the intensities of the two beams of light, incident on the rotatable polarizing disc, from the two arms respectively are equal then the average luminance of the displayed colour is independent of the orientation of the disc.

The hub of the rotatable disc is coupled to the shaft of a Selsyn servo-motor by a friction belt (see Fig. 3(*b*)). The servo-motor is connected by a length of cable to an identical (master) servo-motor within reach of the observer who can then, by rotating the servo-motor shaft, remotely control the magnitude of the colour variations when carrying out the subjective experiments.

Provision is made for the insertion of an additional filter between the disc polarizer, R, and the viewing screen.

The dielectric beam-splitting mirror, M, consists of a single-layer of titanium dioxide on glass, giving a nearly uniform spectral reflexion characteristic with a reflexion coefficient of approximately 0·4 for unpolarized light. The rear surface of the glass is anti-reflexion coated.

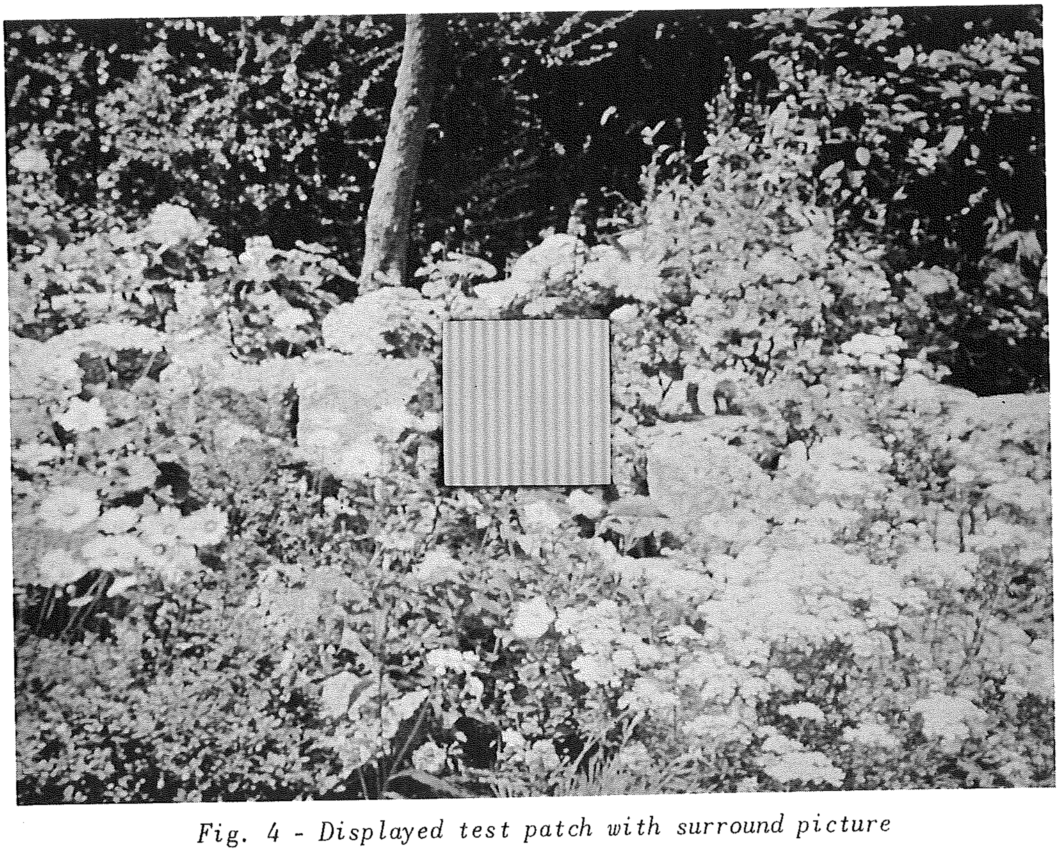


Fig. 4 - Displayed test patch with surround picture

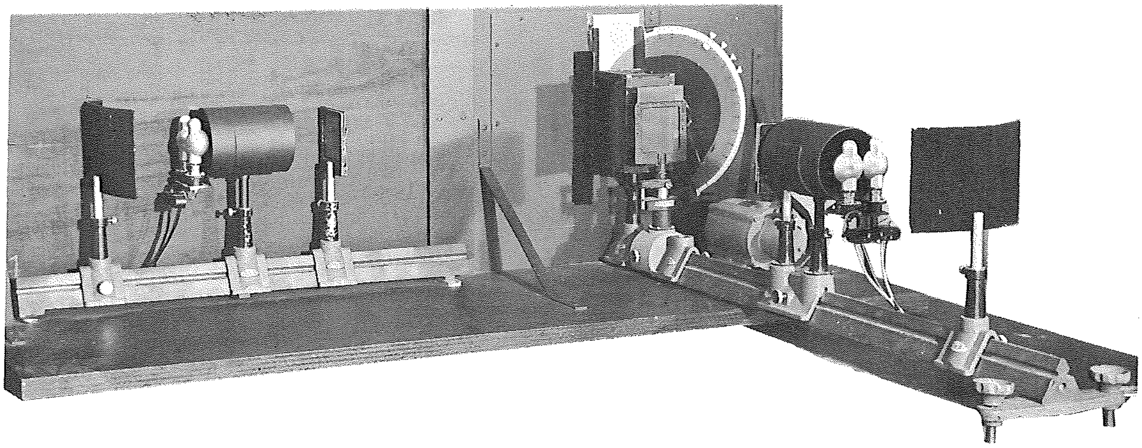


Fig. 5 - Photograph showing rear view of apparatus

From the position of the observer, the small viewing screen on which the pattern appears (by back projection) is centrally located in the cut-out part of a much larger viewing screen, 12 in. × 16 in. (300 mm × 400 mm). This larger surrounding screen is opaque with a matt-white surface suitable for front projection. In some of the subjective experiments a colour slide was projected on the surround by a small projector by the side of the observer: a small opaque patch on the colour slide prevented direct illumination of the test area, the latter thus appeared to be inlaid in the picture. Fig. 4 is a black and white photograph of the display under these conditions as seen by the observer.

Fig. 5 shows a rear view of the optical apparatus. Stray light from the apparatus is shielded from the observer by curtains and opaque (black) screens.

The theoretical basis of the methods described in this section is given in the Appendix.

2.3. Calibration and Adjustment

Careful adjustment of the illumination is necessary to obtain the required conditions uniformly over the test area of the display. In the main-arm of the apparatus the grating-to-screen separations and the lamp separation are adjusted so that the two positions of the grating producing the required forms of colour variation can be established. The projector lamps used were 8V 50W pre-focus type, having a small compact filament and internally silvered glass envelope. These lamps have the advantage of a high normal intensity but the uniformity of illumination is sometimes poor and a certain amount of lamp selection was necessary The operating voltage of one of the pair of lamps in each arm of the apparatus is adjustable by means of a Variac autotransformer in the primary circuit. This facility was used to obtain a fine adjustment of the luminance equality of the two colour primaries forming the displayed colour (the coarse adjustment of luminance equality was achieved by combining neutral density filters with the colour filters).

A visual test of the correct configuration of lamps, grating and screen was used to establish the required display conditions. For checking the chromaticity-

only condition the colour filters in the main-arm (F_1 and F_2 in Fig. 3(*a*)) were removed and the polarizing disc R set for maximum attenuation of the side-arm illumination. The lamp separation was then adjusted until a condition of uniform screen illumination (zero pattern visibility) could be obtained when the relative lamp intensities were correctly adjusted for equality. Due to some slight distortion of the photographic sine-wave grating available, giving rise to a second harmonic component in the spatial frequency spectrum, a precisely uniform field was never obtained and a very faint pattern (at twice the fundamental grating frequency) was always visible at a close viewing distance. The amplitude of this finer pattern was, however, too small to have a significant influence on the results of the experiments, at the viewing distances used.

For checking the luminance-only condition the colour filters were re-inserted and, by means of a photo-electric photometer placed over the front of the small viewing screen, the relative lamp intensities were re-adjusted until equal luminances at the screen were obtained (i.e. identical photometer outputs when either of the lamps is totally obscured). The photometer was then removed and the sine-wave grating moved towards the screen until no chromatic variation could be detected by close visual inspection: the latter check is very sensitive as a small positional error of the grating produces colour fringing.

The photometer mentioned above was a G.E.C. photo-electric photometer, using a Preston liquid filter to obtain a spectral sensitivity characteristic close to the C.I.E. photopic response for the standard observer. This photometer was used for all adjustments of luminance equality.

The final setting-up procedure was to adjust the screen illumination of the pair of lamps in the side-arm of the apparatus. As previously mentioned the colour filters in the side-arm are identical to those in the main-arm. Hence, by adjusting the relative lamp intensities for equal screen luminance the chromaticity of the displayed colour due to the side-arm alone then matched that of the main-arm alone. The final adjustment was to ensure that no change of mean luminance of the displayed colour occured when the polarizing disc, R, was rotated. This was achieved by moving the complete lamp and filter assembly on the side-arm along an optical bench thus increasing or decreasing its contribution to the total screen luminance until, on rotation of the polarizing disc, the minimum variation in photometer output was obtained. (At the optimum point a total variation in mean luminance of approximately 2% was obtained.)

2.4. Apparatus Calibration

The variation in the luminance, V_p, across the viewing screen, due to each 'primary' source in the main-arm can be expressed in the form,

$$V_p = \overline{V}_o \left[1 + m \sin(2\pi f x + \beta)\right] \sin^2\theta \qquad (1)$$

where $\overline{V}_o$ is the mean luminance when $\theta = 90°$

f is the spatial frequency of the pattern on the screen

x is the horizontal distance from an arbitrary origin

β is the phase at the origin

m is the modulation coefficient

θ is the angular displacement of the rotatable polarizing disc from the position giving zero illumination.

The luminance, V_s, due to the corresponding 'primary' source in the side-arm is simply given by,

$$V_s = \overline{V}_o \cos^2\theta \tag{2}$$

if the maximum luminance is adjusted to equal $\overline{V}_o$. The total luminance, V, due to each corresponding pair of 'primary' sources (i.e. a source in the main-arm and its identical twin in the side-arm) is, by adding equations (1) and (2),

$$V = V_p + V_s$$

or

$$V = \overline{V}_o\ (\cos^2\theta + \sin^2\theta) + [\overline{V}_o m \sin(2\pi fx + \beta)] \cdot \sin^2\theta$$

$$V = \overline{V}_o\ [1 + (m \sin^2\theta) \sin(2\pi fx + \beta)]$$

We note that the effective modulation coefficient of the sinusoidal luminance variations is now ($m \sin^2\theta$), and that the mean luminance is independent of θ. Although θ can be read directly from the angular scale of the rotatable polarizer, the maximum value of modulation coefficient, m, must be pre-determined. Its value is controlled by many factors, the main ones being filament size, sine-wave grating contrast and diffusion in the opal-glass viewing screen. The measurement was carried out using a photo-electric scanning method. An aerial image of the displayed pattern was formed by a high-quality enlarging lens and this image was scanned laterally with a fine slit aperture behind which was a photomultiplier tube. The modulation coefficient was then deduced from the maximum and minimum output readings of the photomultiplier. An average value of 0·33 for m was obtained with the grating in the luminance-only position and a value 0·295 with the grating in the chromaticity-only position. (The lower value of m for the latter position is because of the larger grating-to-screen separation.) Fig. 6 shows the calibration curve relating the effective modulation coefficient of the displayed colour variations to the angular setting of the rotatable polarizing disc.

Measurements of the absolute luminances of the test colours used in the experiments were carried out using a 'Spectra' photo-electric photometer.

2.5. Subjective Tests

Two series of subjective tests were conducted, the main difference between these series being the viewing distance. In each series, a test colour was displayed and each of ten observers, in turn, made a number of visual equality judgments as described in Section 2.5.4 below. In the first series the observers sat at a distance of 6 ft (1·8 m) from the viewing screen. At this distance each cycle of the sinusoidal test pattern subtended an angle of 9 minutes of arc (6·7 cycles/degree) at the observer's eye, and the angular size of the total test area (not including the surround screen) was approximately $2^\circ \times 2^\circ$. In the second series the viewing distance was reduced to 2 ft (0·6 m), at which distance each cycle of the pattern subtended an angle of 27 minutes of arc (2·2 cycles/degree) and the angular size of the test area was $6^\circ \times 6^\circ$. For comparison, in television terms, the angular spatial frequency of the observed pattern, in the first series, is approximately equivalent to

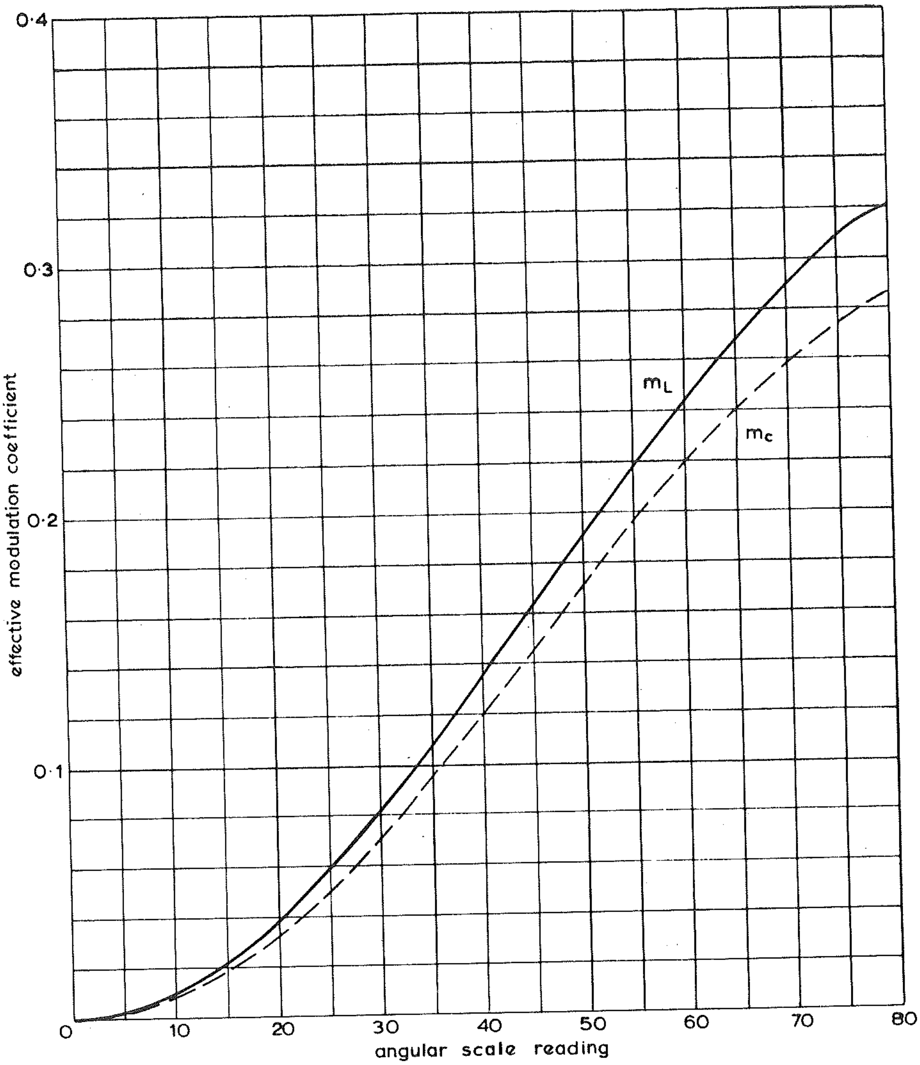


Fig. 6 - Calibration data for the pattern-visibility control

m_L = modulation coefficient luminance-only variations
m_C = modulation coefficient chromaticity-only variations

that produced by a 1·65 Mc/s video signal component on a television monitor working on the United Kingdom 625-line standard viewed at 6 × picture height and, in the second series, to a video signal of 0·55 Mc/s.

2.5.1. Observers

Nine of the ten observers taking part in the experiments in the first series were colour-normal. The one exception appeared to be partially red-green blind, according to the Ishihara colour blindness tests, and was deliberately included. All the observers were male engineers varying in age from 20 to 47 years: four of them had corrected vision. With one or two exceptions the same group of observers took part in the second series of experiments.

TABLE 1

TEST COLOUR					MIXTURE PRIMARIES
NO.	NAME	CHROMATICITY		ABSOLUTE LUMINANCE	
		u	*v*	(ft-L)	
1	Orange	0·402	0·358	3	Red/Yellow
2	Lime green	0·179	0·376	5	Green/Yellow
3	Bluish green	0·089	0·333	4·5	Green/Cyan
4	Dark blue	0·129	0·21	0·5	Blue/Cyan
5	Purple	0·242	0·193	0·5	Blue/Magenta
6	Pink	0·344	0·338	5	Red/Cyan
7	Pale green	0·19	0·338	5·5	Cyan/Yellow
8	Pale pink	0·282	0·329	2	Green/Magenta

2.5.2. Test Colours

Eight test colours were used in the experiments. Their chromaticities, and those of the pairs of 'primary' sources from which each of the test colours were derived, are shown in the C.I.E. - U.C.S. diagram of Fig. 7. The chromaticities of

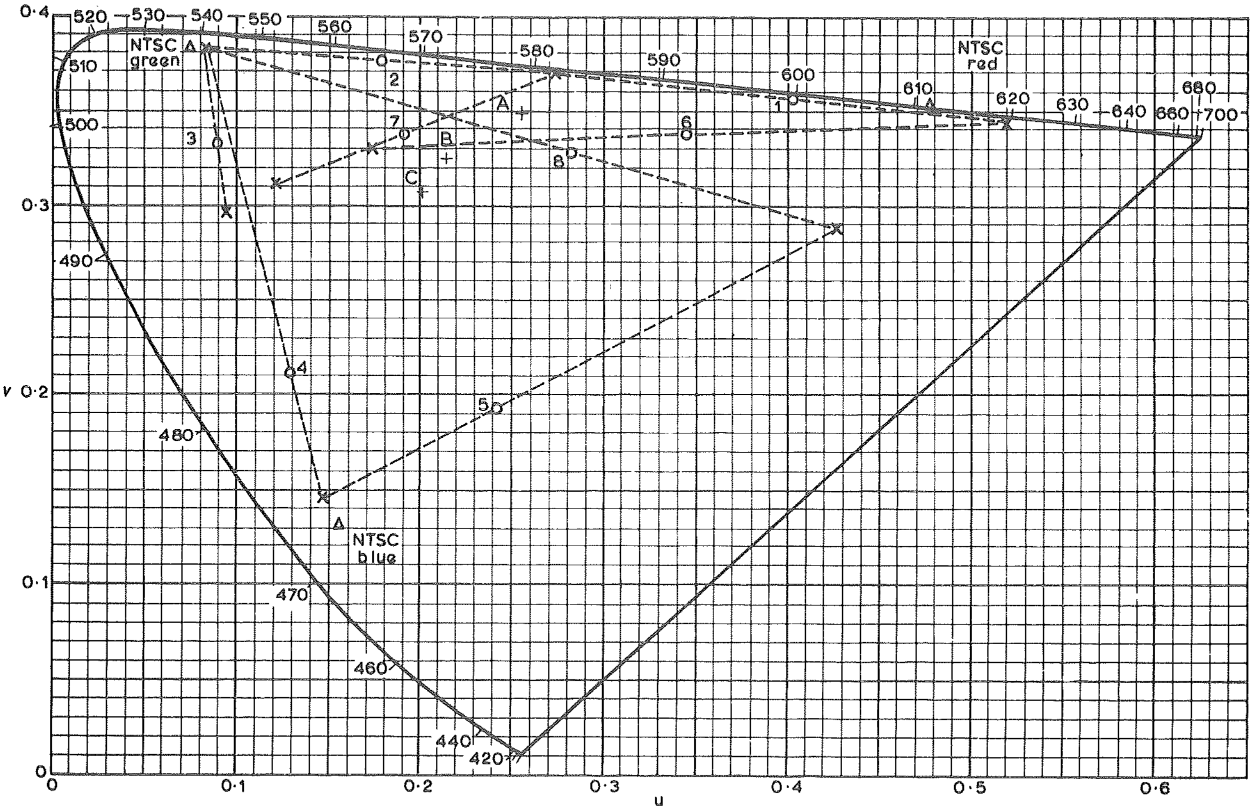


Fig. 7 - Chromaticities of the eight test colours and their associated primaries. (The dashed lines show the directions of the chromatic variations.)

the NTSC colour television primaries (old phosphors) are also plotted on this diagram for comparison of the chromaticity gamut investigated. The test colours 1 to 5 are highly saturated colours and the displayed spatial variations in chromaticity using these colours correspond to variations in hue. The test colours 6 to 8 are desaturated colours. Table 1 lists the test colours, their chromaticities and their absolute luminances. It should be pointed out that, because of the limited number and spectral characteristics of the colour filters available, it is difficult to obtain suitable pairs of 'primary' sources which will, when adjusted for luminance equality, produce test colours having chromaticities and absolute luminances exactly as desired. For example, it was not possible to obtain with the filters available a desaturated blue colour having an absolute luminance greater than about 0·5 foot-Lambert.

The chromaticities of the test colours were deduced from spectrophotometric measurements on the colour filters used in the apparatus, and from a measurement of the effective colour temperature of the 'white' display when the colour filters were removed: the effective colour temperature was approximately that of Standard Illuminant A, i.e. 2850°K.

2.5.3. Surround Picture

In the first series each equality matching by an observer was repeated with the test area surrounded by a colour-picture of a garden scene (see Fig. 4) obtained by optical projection of a 2 in. × 2 in. colour slide. The projector was situated slightly behind and to the side of the observer. A small opaque square patch on the slide prevented direct illumination of the test area of the viewing screen as mentioned in Section 2.2. The peak-white areas of the surrounding picture had a luminance of 10 ft-L. With the projector on, the luminance of the test area due to lens flare and ambient illumination was 0·04 ft-L: the luminance due to the ambient alone was 0·02 ft-L. The ambient illumination was mainly due to a small bench lamp behind the observer: the room was otherwise dark. In the second series of experiments the surround picture was not used.

2.5.4. Test Procedure

(a) First Series

A test colour was displayed and the grating position set to produce luminance-only variations. An observer,* seated with access to the manual control of the pattern visibility, was asked to rotate the control until the luminance-only variations were just-perceptible. This setting was recorded and the grating, starting with the control in a zero-visibility position, was then moved to the position which produced chromaticity-only variations, and the observer again rotated the control until these variations were just-perceptible: the new setting was recorded. The grating was then returned to the luminance-only position and the observer asked to set the control so that the pattern appeared to him quite-definitely-perceptible. No restriction was placed on his interpretation of this criterion. Then, with the grating moved back to the chrominance-only position, he was asked to adjust the control to produce a pattern which he judged to be equally visible. If the observer wished, he was allowed to return to the luminance-only condition and start again, perhaps selecting a slightly different reference level from that chosen previously. His final pair of settings were recorded.

* The observer was previously given two or three minutes to adapt himself to the test conditions.

The above procedure was repeated but with the surround illuminated with the colour picture.

After the ten observers had carried out, in turn, the required tests, another test-colour was set up.

(b) Second Series

In this series, the observers were seated at a much closer viewing distance but the basic procedure was identical with that outlined above. No surround picture was present in this series. The visual matchings for the two criteria, i.e. just-perceptible and quite-definitely-perceptible, were recorded for each of the following conditions of the experiments:

(i) with the test-colour at approximately the absolute luminance level used for that colour in the first series.

(ii) with the absolute luminance level reduced to two fifths of the above values respectively. (This reduction was chosen to give an average test-colour luminance equal to that obtained in condition (iii) below.)

(iii) with the luminance of the displayed colour vertically perturbed by placing a second sinusoidal grating (horizontally oriented) immediately behind the opal-glass viewing screen. (The magnitude of the vertical perturbations was thus fixed, and was approximately equal to that of the maximum luminance-only variations obtainable in the horizontal direction.)

The sequence in which these three tests were carried out was varied from observer to observer.

Four test-colours (nos. 1, 3, 5, 7 of the eight used in the first series) were used in the second series.

3. RESULTS

3.1. Sensitivity Ratio

The results are presented here in terms of the $(V,\ u,\ v)$ colour space outlined in the introduction. The visual sensitivity ratio (luminance/chromaticity) is here measured by the ratio (denoted by ϕ)

$$\phi \equiv \frac{\delta V/V}{\delta(u,v)}$$

where δV is the peak-to-peak magnitude of the sinusoidal variation of the luminance and V is the mean value. $\delta(u,v)$ is the (peak-to-peak) excursion of the sinusoidal chromaticity variation judged to be visually equivalent. This particular ratio was chosen because in addition to being non-dimensional both the numerator $\delta V/V$ and the denominator $\delta(u,v)$ were not expected to vary in value to any great extent over the limited region of the (V,u,v) colour space investigated. Hence, their ratio ϕ is likely to be almost invariant over this region of colour space.

Where the results are averaged for the ten observers taking part in the experiment the sensitivity ratio will be denoted by:

$$\phi_{av} \equiv \frac{(\delta V/V)\mathrm{av}}{\delta(u,v)_{av}}$$

The sensitivity ratio can be deduced from the recorded pair of modulation coefficients, corresponding to the pair of control settings selected by an observer in a single equality judgment. Let the selected modulation coefficient for the luminance-only variations be m_L and the visually-equivalent coefficient for chromaticity-only variations be m_c then

$$\frac{\delta V}{V} = 2m_L$$

and it may be shown that providing m_c is not too large ($m_c < 0{\cdot}3$ say),

$$\delta(u,v) = m_c \left[\frac{4v_1v_2}{(v_1 + v_2)^2}\right] \left[(u_2 - u_1)^2 + (v_2 - v_1)^2\right]^{1/2}$$

with sufficient accuracy, where (u_1, v_1) and (u_2, v_2) are the chromaticity co-ordinates of the two 'primaries', respectively, forming the displayed test colour. The last term in the expression for $\delta(u,v)$ is simply the chromatic separation, on a (u,v) chromaticity diagram, of the two primaries involved. The first term in square brackets arises because the displayed chromaticity does not, in general, bisect the line on a chromaticity diagram joining the two 'primaries', even though the latter contribute equally to the total luminance of the displayed colour.

Thus we obtain

$$\phi \equiv \frac{\delta V/V}{\delta(u,v)}$$

$$= \left(\frac{m_L}{m_c}\right) \left[\frac{(v_1 + v_2)^2}{2v_1v_2}\right] \left[(u_2 - u_1)^2 + (v_2 - v_1)^2\right]^{-1/2}$$

3.2. Variation of Sensitivity Ratio with Level of Perceptibility

The results obtained for the first few test colours showed clearly that for the majority of the observers the sensitivity ratio ϕ depended on the magnitude of $(\delta V/V)$ i.e. ϕ is a function of the magnitude of the luminance-only variation selected as the reference level against which the chrominance-only variation was matched. Fig. 8 illustrates the extent of this dependence for one of the test colours, and shows also the spread of individual-observer sensitivity ratios obtained. In this figure, which gives the results for each of the ten observers, ϕ is plotted against $(\delta V/V)$ using logarithmic co-ordinate scales: the experimental conditions and test

colour are indicated on the figure. Fig. 8(*a*) shows the individual results obtained at 6 ft viewing distance (6·7 cycles/degree) and Fig. 8(*b*) refers to the closer viewing distance (2·2 cycles/degree). Each plot point is the result of one observer match; the triangles refer to the just-perceptible criterion and the circles to the quite-definitely-perceptible criterion, the pair of points obtained by each observer being linked by a straight line. The solid triangles and circles shown on the figure are the average values of the sensitivity ratios, i.e. ϕ_{av}, for the two criteria respectively: the vertical solid lines through these mean values indicate the estimated standard errors of the mean values.

It will be seen from the results that, notwithstanding some exceptions, there is a definite tendency for the visual sensitivity ratio to increase as the level of perceptibility of the luminance variations increases. This was found to be true for all the colours investigated. Consequently, one may infer that the perceptibility of chromaticity-only variations increases with their magnitude at a faster rate than does the perceptibility of luminance-only variations.

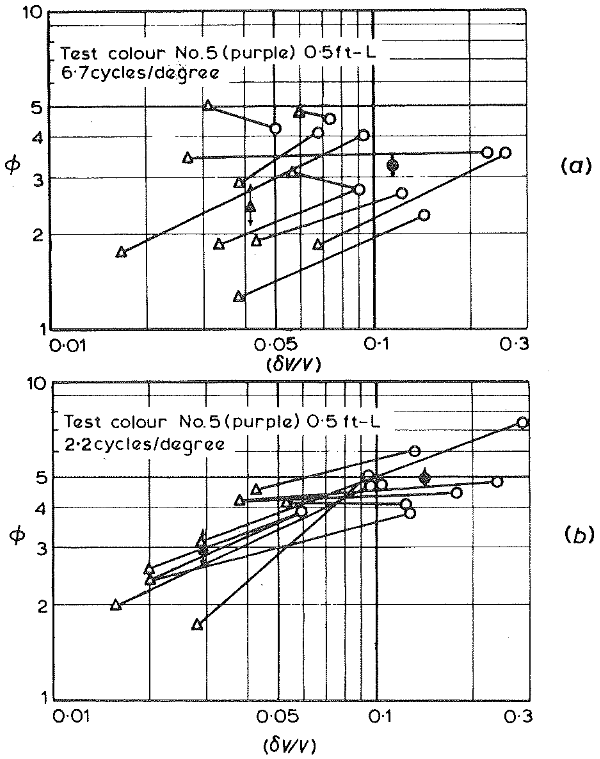


Fig. 8 - Individual observer sensitivity ratios as a function of perceptibility

(*a*) 6·7 cycles/degree (*b*) 2·2 cycles/degree

Δ just-perceptible criterion
O definitely-perceptible criterion
mean with ± S.E.

A reduction in the spread of sensitivity ratios for the definitely-perceptible criterion is also manifest in Fig. 8.

3.3. Variation of Sensitivity Ratio with Test-Colour

The observer-averaged sensitivity ratios, ϕ_{av}, as a function of the relative luminance variation are shown in Figs. 9(*a*) and 9(*b*) with test colour as parameter. The plot points in these figures now represent average values for the ten observers. The numbers on the lines joining the pairs of plot points denote the test-colour to which the values refer (see Fig. 7). Fig. 9(*a*) relates to the 2 ft viewing distance and Fig. 9(*b*) to the 6 ft viewing distance.

The average sensitivity ratio at a given level of perceptibility does not appear to vary greatly with the chromaticity of the colour or the direction of the chromaticity variations. This is, of course, the general result one might expect if the properties of the C.I.E. uniform chromaticity scale hold for cyclic, spatial, fluctuations of colour as well as for chromatic differences between two juxtaposed (large) coloured fields. Test colour no. 7 seems to be a significant exception:

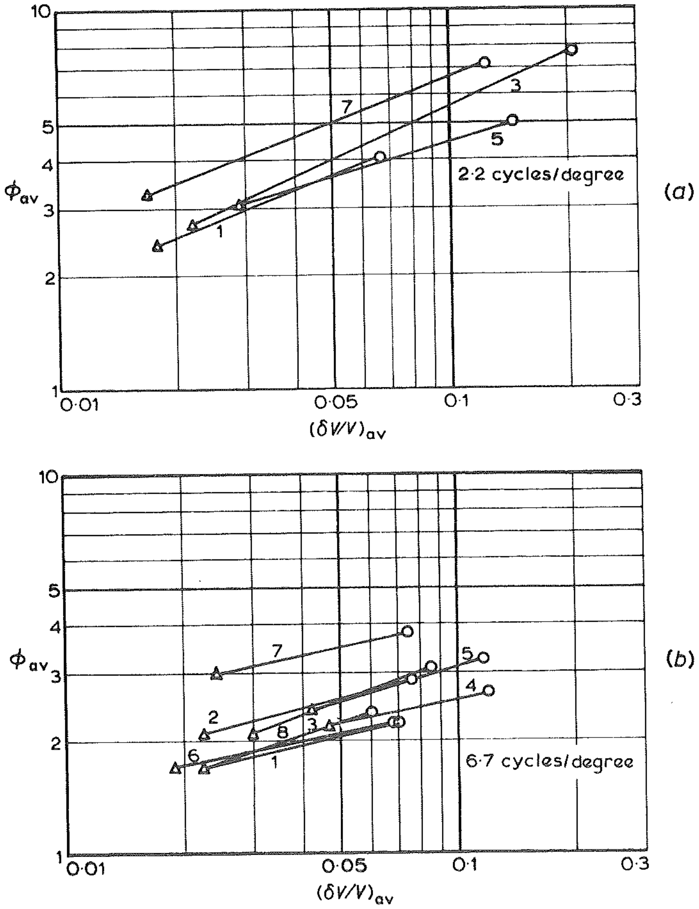


Fig. 9 - Observer-averaged sensitivity ratios for the eight test colours

(*a*) 2·2 cycles/degree (*b*) 6·7 cycles/degree

Δ just-perceptible criterion

O definitely-perceptible criterion

this colour was a desaturated lime-green with chromaticity variations in the yellow to cyan direction. Inspection of the results for this particular colour shows that the increase in sensitivity ratio is due to the somewhat lower value of $\delta(u,v)_{av}$ obtained for this colour rather than to an increase in the $(\delta V/V)_{av}$ value, (see Section 4). For instance, the average $\delta(u,v)$ value for this colour corresponding to the just-perceptible criterion is approximately two-thirds that of the average of all the colours tested.

It is shown later that a significant dependence of the sensitivity ratio on the absolute luminance of the test colour was found, hence some modification of the results shown in Fig. 9 might be expected if the experiment had been carried out with the test colours at the same absolute luminance. Nevertheless, the test colours used had approximately the relative luminances that might be encountered in natural scenes, e.g. highly saturated blue or purple colours do not usually occur at such high luminances as saturated orange or yellow-green colours in the same scene.

3.4. Variation of Sensitivity Ratio with Viewing Distance

The general increase in the average sensitivity ratio when the viewing distance is reduced, seen by comparing Fig. 9(*a*) with Fig. 9(*b*), was expected because it is well known that the perceptibility of chromatic differences diminishes with increasing viewing distance at a faster rate than does the perceptibility of luminance differences.

The increase in average sensitivity ratio is approximately 50% when changing the viewing distance from 6 ft to 2 ft, which corresponds to decreasing the angular spatial frequency of the pattern display from 6·7 cycles/degree to 2·2 cycles/degree.

3.5. Effect of Surround Picture

Fig. 10 shows the effect of the surround picture on the average sensitivity ratio ϕ_{av}, for each of the eight test colours (first series). The dashed-lines refer to the results obtained with the surround colour-picture displayed.

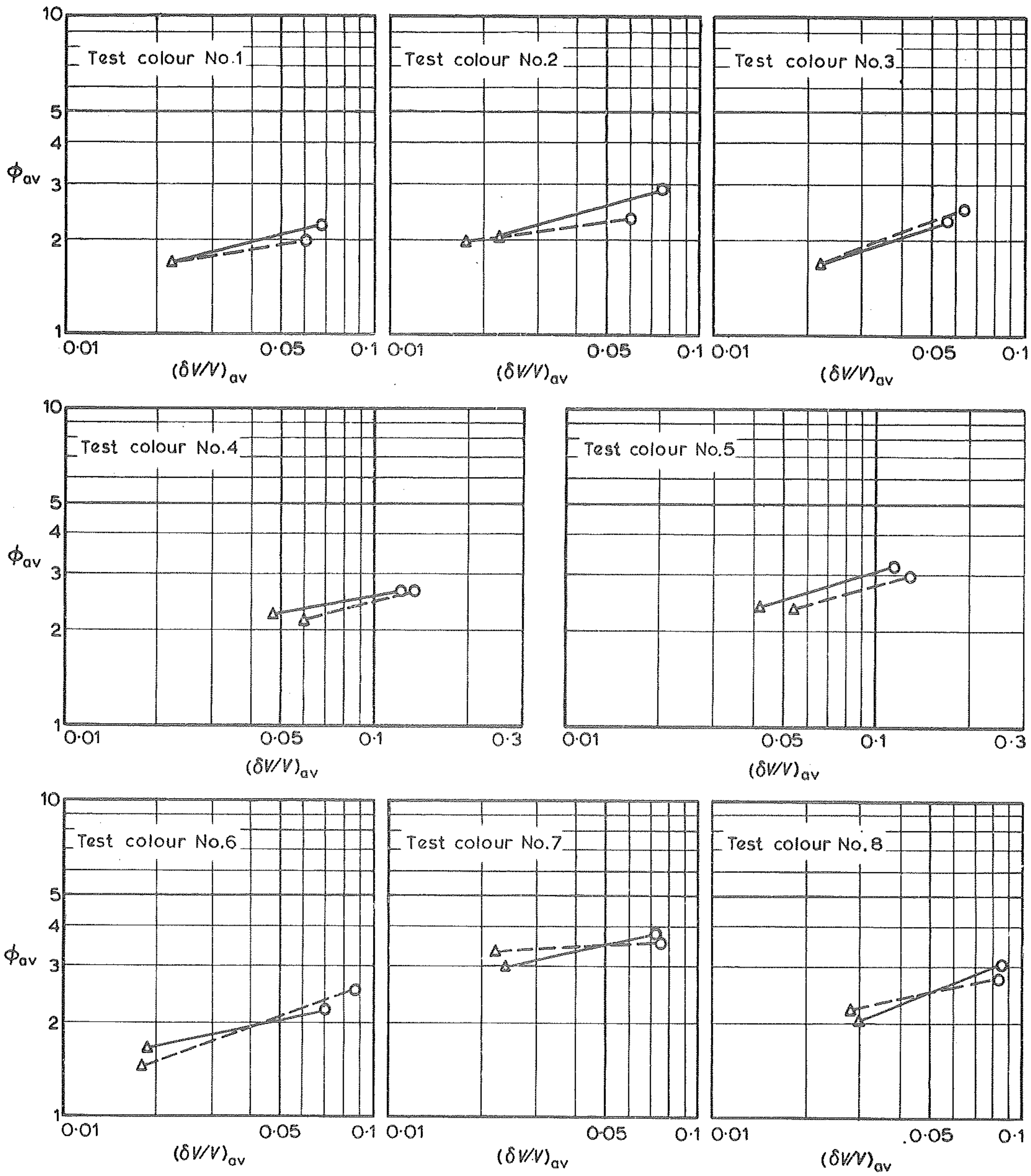


Fig. 10 - Effect of surround picture on observer sensitivity ratio

——— without surround picture
– – – with surround picture

Δ just-perceptible criterion
O definitely-perceptible criterion

There appears to be no systematic difference between the results obtained with or without the surround picture.

3.6. Variation with Luminance

In the second series, results were obtained for each of the four test colours at two levels of absolute luminance, the lower level in each case being two-fifths of the higher. The effect of this luminance change on the average sensitivity

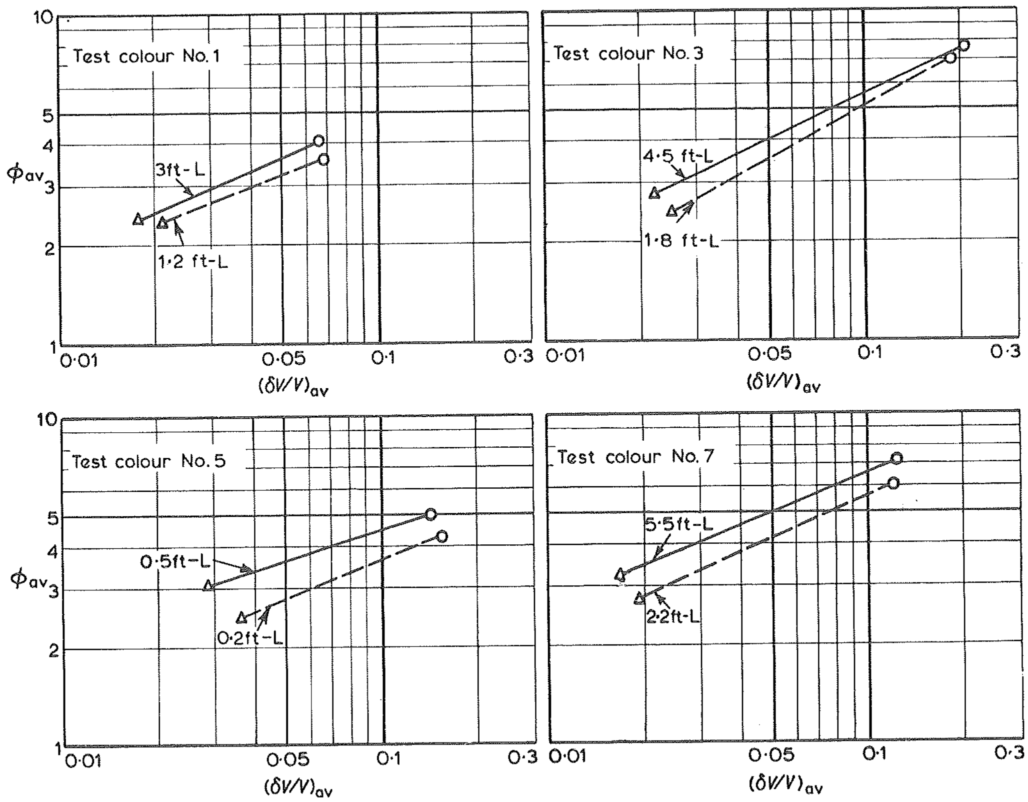


Fig. 11 - Effect of absolute luminance on the average sensitivity ratios

Δ just-perceptible criterion
O definitely-perceptible criterion

ratios is shown in Fig. 11, where the dashed-lines refer to the lower luminance level and the full lines to the higher.

These results show that the sensitivity ratio is dependent on the absolute luminance of the colour: reducing the luminance produces a relatively greater reduction in sensitivity to chrominance-only variations than to luminance-only variations, hence ϕ is reduced at a given level of $(\delta V/V)$. A more detailed experiment is required to establish a working empirical relationship between absolute luminance and sensitivity ratio.

3.7. Effect of Vertical Luminance Perturbations

In all the experiments described so far there was no variation in the vertical direction (i.e. parallel to the grating lines) of either the chromaticity and or luminance of the test-colour. The effect on the sensitivity ratio of introducing a further sine-wave grating in the optical path, at right-angles to the main grating, in order to perturb the luminance in the vertical direction was investigated. The extra grating had a spatial frequency and effective modulation coefficient similar to that of the main grating and was placed immediately behind the small viewing screen. Thus, in this position, the magnitude of the luminance perturbation of the test colour in the vertical direction remained constant and independent of the adjustable control which varied the pattern visibility in the horizontal direction only. When the

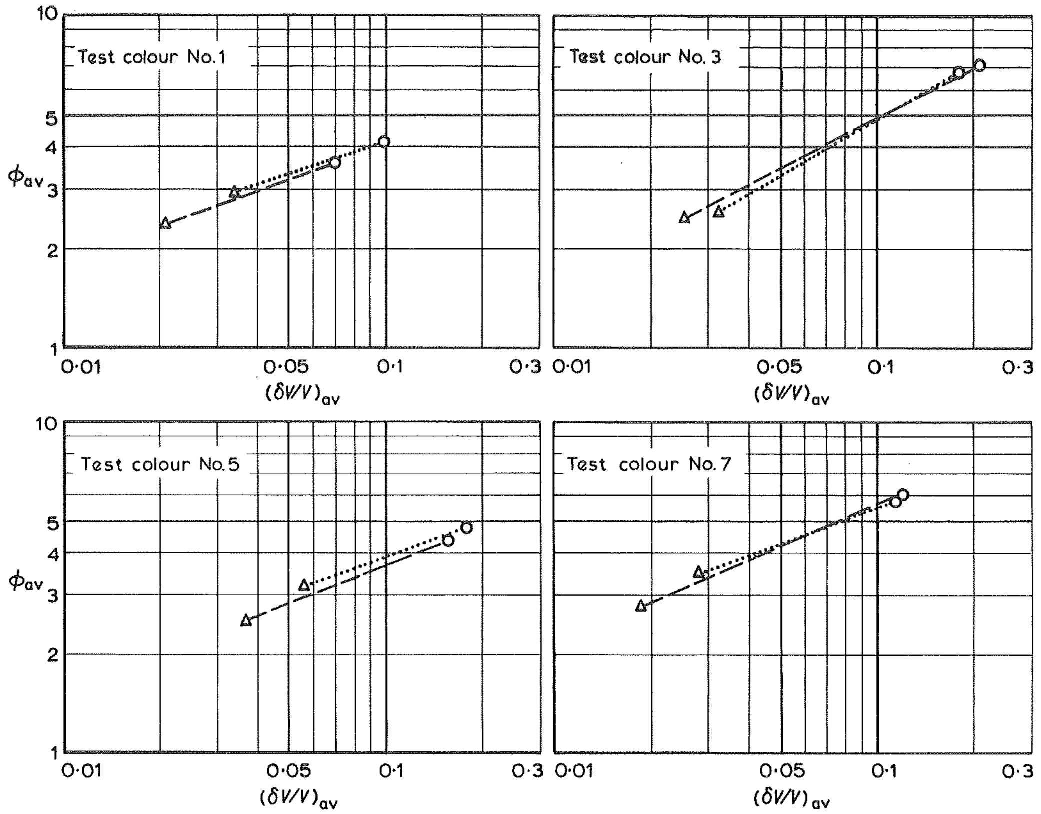


Fig. 12 - Effect of vertical luminance perturbations on the sensitivity ratio

.... with vertical luminance perturbation
— — — — 'constant' vertical luminance

Δ just-perceptible criterion
O definitely-perceptible criterion

control setting was at the position of maximum visibility, and the main sine-wave grating in the position giving rise to luminance-only variations, the displayed pattern had a chequer-board appearance.

The results of this experiment for four test colours are shown in Fig. 12, where the dotted lines refer to the display with the vertical luminance perturbation. These results may be compared with those (shown by the dashed lines in Fig. 12) obtained when the display is uniform in the vertical direction but has the same mean luminance. It will be noticed from these results that the presence of the vertical luminance perturbation significantly increases the threshold value of $(\delta V/V)_{av}$ corresponding to the only-just-perceptible criterion. The sensitivity ratio ϕ_{av} however, is not greatly modified for a given value of $(\delta V/V)_{av}$ in the overlap region.

4. FURTHER ANALYSIS OF THE RESULTS

Although the emphasis in the experiments was on the measurement of the sensitivity ratio ϕ, it is interesting to examine the measured variation of the just perceptible difference in chromaticity $\delta(u,v)_{av}$ with respect to test colour. Table 2 shows the threshold values (averaged for the ten observers) of $\delta(u,v)$ corresponding to the only-just-perceptible criterion.

TABLE 2

These results refer to the larger viewing distance without surround picture

NO.	TEST COLOUR			J.P. THRESHOLD VALUE OF $\delta(u,v)_{av}$* (C.I.E.-U.C. UNITS)
	DESCRIPTION	DIRECTION OF CHROMATIC VARIATION	LUMINANCE ft-L.	
1	Orange	Red - Yellow	3	0·013
2	Lime-Green	Green-Yellow	5	0·010
3	Bluish Green	Green - Cyan	4·5	0·013
4	Dark Blue	Blue - Cyan	0·5	0·021
5	Purple	Blue - Magenta	0·5	0·018
6	Pink	Red - Cyan	5	0·011
7	Pale Green	Cyan - Yellow	5·5	0·008
8	Pale Pink	Green - Magenta	2	0·014
				Mean value 0·0135

* peak-to-peak excursion

Fig. 13 shows the data in Table 2 plotted on a C.I.E. - U.C. diagram: the solid lines through the plot points show the extent of the sinusoidal chromaticity deviations (peak-to-peak) corresponding to the just-perceptible criterion.

It will be seen from the figure and from Table 2, that the measured maximum variation of the just-perceptible chromatic differences for the test colours investigated is slightly greater than 2·5 : 1. However, if allowance were made for the differences in the absolute luminances of the test colours, it is expected that the variation would be reduced considerably. Hence, the present results relating to sinusoidal chromaticity variations provide further evidence of the approximate uniformity of the C.I.E. uniform chromaticity scale. It is possible that the low value of 0·008 C.I.E. units obtained for test colour no. 7 indicates that a substantial change may occur in the properties of the C.I.E. uniform chromaticity scale when the colour variations are between areas subtending very small angles at the eye. Test colour no. 7 had chromatic variations in the yellow to cyan direction and the result obtained for this colour would support the conclusions of earlier researches that, for medium detail in pictures, chromatic discrimination tends to be better along the orange to cyan axis of chromaticity (a fact which led to the adoption of the wide-band I signal in the NTSC colour television system).

Fig. 14 gives the values of the just-perceptible chromatic differences averaged for the test colours investigated: for comparison the result obtained by MacAdam using a bipartite field is included.

The average sensitivity ratio, ϕ_{av}, was found to be somewhat dependent on the magnitude of the colour variations (see Section 3.2) and all the results have been

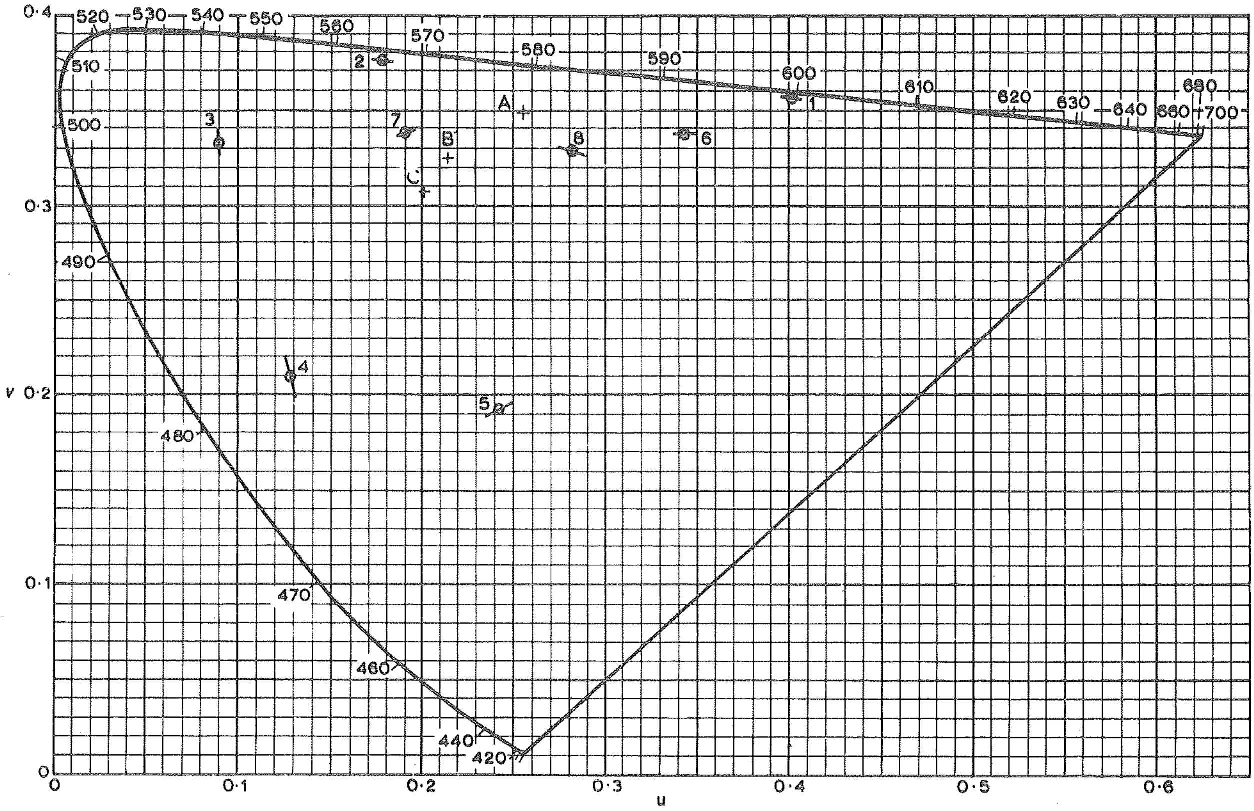


Fig. 13 - Just-perceptible 'peak-to-peak' excursion of a sinusiodal variation in chromaticity. (Spatial frequency 6·7 cycles/degree.) Circles show mean chromaticity, lines through circles indicate direction and magnitude

presented as a function of $(\delta V/V)$. However, the general relation between $(\delta V/V)$ and a six-point subjective scale of perceptibility and annoyance is known, from previous work on co-channel interference and noise in monochrome television,[3, 4] to be approximately 5 dB per grade. Assuming this relation to hold for sinusoidal luminance variations of a coloured field the sensitivity ratios can be expressed in terms of a subjective scale of perceptibility, as shown in Fig. 15. Here the abscissae scale $\delta V/V$ used in the previous figures has been replaced by the reference numbers of the six-point grading scale given in the text below. Thus an increase of one grade represents an increase of 5 dB in $\delta V/V$. Since one criterion in the experiment was that of 'just-perceptible' the average result for this criterion is assumed to be aligned with Grade 2 of the following six-point scale:

TYPE OF CHROMATIC VARIATION		SIZE OF TEST FIELD	AVERAGE LUMINANCE OF TEST COLOURS (ft-L)	$\delta(u, v)$ (C.I.E.-U.C. UNITS)
SINUSOIDAL (6·7 cycles/ degree)	$\delta(u, v)$	2°	3·25	0·0135
SINUSOIDAL (2·2 cycles/ degree)	$\delta(u, v)$	6°	3·40	0·0075
BIPARTITE	$\delta(u, v)$	2°	16·00	0·0038

Fig. 14 - Average just-perceptible chromatic differences for various types of chromatic variation

1. Imperceptible

2. Just-perceptible

3. Definitely-perceptible but not disturbing

4. Somewhat objectionable

5. Definitely objectionable

6. Unusable

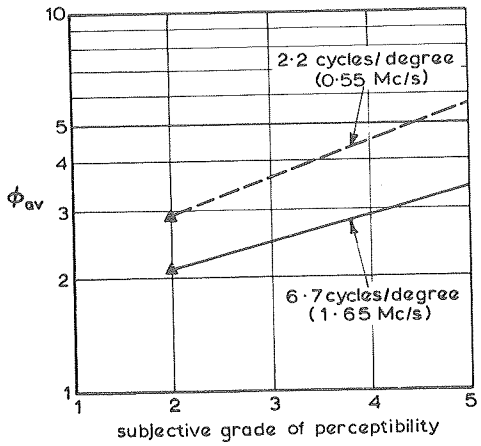


Fig. 15 - Average sensitivity ratios for all test colours as a function of subjective grade of perceptibility

——— 6·7 cycles/degree (1·65 Mc/s)
— — — 2·2 cycles/degree (0·55 Mc/s)

The full line in Fig. 15 refers to the larger viewing distance (angular spatial frequency = 6·7 cycles/degree) and the dashed line refers to the shorter viewing distance (2·2 cycles/degree): also, the lines represent the average sensitivity ratios for all observers and all test colours.

The video frequency of a television signal component which, applied to a 625-line television monitor viewed at 6 × picture height, would give rise to a pattern of equivalent angular spatial frequency is also indicated on the Figure.

It is clear that since ϕ_{av} increases with increasing degree of perceptibility the denominator of ϕ_{av}, i.e. $\delta(u,v)$, must increase at a somewhat lower rate than that of the numerator $\delta V/V$. Thus, from the slopes of the lines in Fig. 15, it may be shown that the relation between the magnitude of chromaticity-only variations and perceptibility is approximately 3·3 dB per grade, compared with the assumed value of 5 dB per grade for luminance-only variations.

5. CONCLUSIONS

1. A general conclusion which may be drawn from the results is that the rate of change of perceptibility with change in absolute luminance, or with viewing distance or with perturbation magnitude is greater for chromaticity-only variations than for luminance-only variations. Consequently the visual sensitivity ratio is somewhat dependent on these factors. The average value of the ratio at the just-perceptible level was found to be in the range 2 to 3.

2. If, as in this report, the chromatic variations are measured on the C.I.E. - U.C. scale, i e. $\delta(u,v)$, then the visual sensitivity ratio appears to be substantially independent of the chromaticity of the colour and the direction of the variations for a given magnitude of perturbation. (Chromatic variations along the cyan to yellow axis may be significant exception to the latter statement.)

3. For a given colour and perturbation magnitude, the visual sensitivity ratio appears to be substantially unaltered by the presence of other colours in the surrounding visual field of the same order of luminance.

4. The sensitivity of the eye to horizontal variations is somewhat reduced by the presence of a simultaneous luminance perturbation (of fixed magnitude) in the vertical direction. However, for a given value of $\delta V/V$ (greater than the threshold value) the sensitivity ratio is unaltered.

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APPENDIX

Theoretical Basis of the Method

Let the colour of the viewing screen due to the spectrally-filtered light flux arriving from one of the projector lamps in the main-arm (say, S_1 in Fig. 3) be C_1. The colour C_1 is substantially uniform over the screen in the absence of the sine-wave grating, and may be completely specified in terms of the C.I.E. - uniform chromaticity colour space by the three tristimulus values U, V, W, where the V value is directly proportional to the luminance of the colour. Thus we can write the colour equation:

$$C_1 = U_1 + V_1 + W_1$$

Similarly, for the colour C_2 due to the flux arriving from the second lamp S_2 we have:

$$C_2 = U_2 + V_2 + W_2$$

Introducing the sine-wave grating between the lamps and the screen produces a spatial variation of the luminance of each colour component, their respective chromaticities remaining constant. Hence, with the grating, the respective colour equations become:

$$C_1 = (U_1 + V_1 + W_1)\ \bar{t}\left[1 + m \sin(2\pi f_s x + \beta_1)\right]$$
$$\text{and } C_2 = (U_2 + V_2 + W_2)\ \bar{t}\left[1 + m \sin(2\pi f_s x + \beta_2)\right]$$

where f_s is the spatial frequency of the sinusoidal variations in a given direction across the screen, $\bar{t}$ is the mean transmission coefficient of the grating, m is the relative amplitude of the sinusoidal variations in the luminance of each colour component (modulation coefficient), β is the phase angle at an arbitrary point (origin) on the screen and x is the lateral distance from this origin in the given direction.

Now the difference between the phase angles of the two components at the origin, i.e. $\beta_1 - \beta_2$, depends on the geometrical disposition of the lamp filaments with respect to the grating and the viewing screen. In the apparatus the phase difference between the two components was adjusted by altering the grating-to-screen separation. If the latter is adjusted so that $\beta_1 - \beta_2$ is an even multiple of π the colour C representing the additive mixture of the two components is given by:

$$C = C_1 + C_2$$

$$\beta_1 = n\pi + \beta_2, \quad (\text{n even})$$

$$\text{i.e.} \quad C = \bar{t}\ \left[(U_1 + U_2) + (V_1 + V_2) + (W_1 + W_2)\right]\ \left[1 + m \sin(2\pi f_s x + \beta_1)\right]$$

It will be noted that, for this condition, the colour variation is one of luminance-only, the chromaticity being independent of x.

Alternatively, by moving the grating to another position such that $\beta_1 - \beta_2$ is an odd multiple of π the above colour equation becomes:

$$C = \bar{t} \left\{ \left[(U_1 + U_2) + (U_1 - U_2)\, m \sin(2\pi f_s x + \beta_1) \right] + \left[(V_1 + V_2) + (V_1 - V_2)\, m \sin(2\pi f_s x + \beta_1) \right] + \left[(W_1 + W_2) + (W_1 - W_2)\, m \sin(2\pi f_s x + \beta_1) \right] \right\}$$

If, in addition, the mean luminances of the two components are adjusted to be equal, i.e. if $V_1 = V_2 = V$ in the above equation, then:

$$C = \bar{t} \left\{ \left[(U_1 + U_2) + (U_1 - U_2)\, m \sin(2\pi f_s x + \beta_1) \right] + \left[2V \right] + \left[(W_1 + W_2) + (W_1 - W_2)\, m \sin(2\pi f_s x + \beta_1) \right] \right\}$$

Thus providing that the two components have different chromaticities the colour variation on the screen will now be one of chromaticity-only, the luminance remaining constant.

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